2.2 VISCOSITY

Summary

The recommended values for the dynamic viscosity of liquid sodium in Pa·s are given in Table 2.2-1. For the temperature range 371 to 2500 K, the natural logarithms of the dynamic viscosity have been calculated from the equation recommended by Shpil'rain et al.:[1]

$$\ln \eta = -6.4406 - 0.3958 \ln T + \frac{556.835}{T} \quad . \tag{1}$$

The recommended value for the viscosity of sodium at the critical point, 5.8 x 10^{-5} Pa·s, is the value recommended by Bystrov et al.[2] for the critical temperature of 2503 K. It was calculated using the method of Andrade[3] by Shpil'rain et al.[1] in their assessment of the methods to calculate the viscosity at the critical point.

Figure 2.2-1 shows the recommended values for the viscosity of sodium with the uncertainties as dashed lines. The uncertainties are given in Table 2.2-2.

Discussion

The recommended equation for the viscosity of liquid sodium is from the assessment by Shpil'rain et al.[1] The measurements of the viscosity of liquid sodium[4-18] included in the assessment are shown in Table 2.2-3. In their least squares fit to the data, Shpil'rain et al. excluded data from the experiments by Sauerwald, by Gering and Sauerwald, by Godfrey, and by Achener because the purity of the sodium used in these experiments was unknown and these data have greater scatter than data from other experiments. The form of equation used to fit the data was based on the theory given by Frenkel.[19] In their data assessment, Shpil'rain et al. checked the consistency of their recommended equation as it approached the critical point with vapor viscosities from two sets of calculations. They compared values for the viscosity at the critical temperature, 2503 K, calculated using an Andrade equation, corresponding states, the free volume theory, and the average diameter. Values ranged from 0.5 x 10^{-4} Pa·s to 0.99 x 10^{-4} Pa·s. In their review of properties of the alkali metals, Bystrov et al.[2] recommended 0.58 x 10^{-4} Pa·s for the viscosity of sodium at the critical point. This is the value obtained by Shpil'rain et al. using an Andrade equation of the form

Table 2.2-1 Recommended Values for the Dynamic Viscosity of Liquid Sodium

Temperature (K)	**Viscosity x 10^4 (Pa·s)**
371	6.88
400	5.99
500	4.15
600	3.21
700	2.64
800	2.27
900	2.01
1000	1.81
1100	1.66
1200	1.53
1300	1.43
1400	1.35
1500	1.28
1600	1.22
1700	1.17
1800	1.12
1900	1.08
2000	1.04
2100	1.01
2200	0.98
2300	0.95
2400	0.92

$$\eta = K \frac{\sqrt{MT}}{V^{2/3}} \quad , \tag{2}$$

where η, T, V, and M are, respectively, the critical viscosity, critical temperature, critical volume, and molecular weight.

Fink and Leibowitz[20] fit data of Ewing et al.,[8-9] Chiong,[7] Godfrey,[10] Solov'ev,[11] and Fomin and Shpil'rain[14] to an Andrade II equation,[3] which has the form

Table 2.2-2 Estimated Uncertainty in Values for the Viscosity of Sodium Calculated from Eq. (1)

Temperature (K)	**Viscosity x 10^4 Pa·s**	**Uncertainty, $\left(\frac{\delta\eta}{\eta}\right)$ (%)**
$371 \leq T \leq 1500$[a]	$\eta = \exp\left[-6.4406 - 0.3958 \ln T + \frac{556.835}{T}\right]$	3 - 5
$1500 < T \leq 2000$[b]		5 - 10
$2000 \leq T \leq 2500$[b]		10 - 12

(a) $\frac{\delta\eta}{\eta}(\%) = 2.3 + 0.0018\ T$

(b) $\frac{\delta\eta}{\eta}(\%) = -10 + 0.01\ T$

$$\eta = A\ e^{\frac{C}{VT}}\ V^{-\frac{1}{3}} \quad . \tag{3}$$

where A=0.11259, C=749.08, and V=1/ρ_ℓ where ρ_ℓ is the liquid density. They used a technique due to Grosse[21] to extrapolate from the maximum temperature of these data (1300 K) to the critical temperature. Viscosity values calculated by Fink and Leibowitz are compared with the recommended values of Shpil'rain et al. in Fig. 2.2-2. The recommended value of the viscosity at the critical temperature, 2503.7 K, is included in the figure. Deviations of values for the viscosity calculated by Fink and Leibowitz from those given by the recommended equation are shown in Fig. 2.2-3. These deviations are defined as

$$Deviations = \frac{[\eta(F-L) - \eta(Eq.\ 1)]\ 100\%}{\eta(Eq.\ 1)} \quad . \tag{4}$$

Table 2.2-3 Sodium Viscosity Data Assessed by Shpil'rain et al.

Temperature (K)	**Limiting Confidence Error (%)**	**Purity of Sample (Mass %)**	**Authors**	**Year**	**Ref.**
373 373	±25 ±25	— —	Sauerwald	1932 1932	4 5
373 - 456	±25	—	Gering, Sauerwald	1935	6
371 - 628	±1.5	99.8	Chiong	1936	7
377 - 466	±2 - 3	100.0	Ewing, Grand, Miller	1951	8
416 - 959	±3 - 10	100.0	Ewing, Grand, Miller	1954	9
600 - 1152	±15	—	Godfry	1952	10
372 - 1075	±3	99.7	Solov'ev, Novikov	1954	11, 12
1073 - 1773	±10	—	Kalakutskaya	1964	13
481 - 1060	±3	99.5	Fomin, Shpil'rain	1965	14, 15
391 - 1313	±10 - 20	—	Achener	1967	16
373 - 673	±3	99.974	Genrikh, Kaplun	1970	17, 18

The curvature exhibited by the deviations arises from the different functional forms used to represent the viscosity in the two assessments. Within the range of experimental data fit by both groups, the deviations are within 5%, which is less than the estimated uncertainty in some of the data, as indicated in Table 2.2-3. Above 1300 K, the maximum deviation is 7.5%.

The equation derived by the assessment by Shpil'rain et al. is recommended rather than that given by Fink and Leibowitz because it is based on an assessment of more experimental data, which extend to a higher temperature (1774 K) than the data included in the Fink and Leibowitz assessment. Some of the data that were included in the assessment by Shpil'rain et al., which were not available to Fink and Leibowitz, have low estimated uncertainties. In their review of properties of the alkali metals, Bystrov et al.[2] recommend the equation given by Shpil'rain et al.

Uncertainty

The estimated uncertainty in the recommended values range from 3% at the melting point to 5% at 1500 K and increases to 12% at 2500 K. The uncertainties are assumed to increase linearly with temperature. Below 1500 K, the uncertainty is approximated by the linear equation

$$\frac{\delta\eta}{\eta}(\%) = 2.3 + 0.0018\ T \tag{5}$$

$$for\ 371\ K \leq T \leq 1500\ K\ .$$

Above 1500 K, the uncertainty is approximated by

$$\frac{\delta\eta}{\eta}(\%) = -10.0 + 0.01\ T \tag{6}$$

$$for\ 1500\ K \leq T \leq 2500\ K\ .$$

Uncertainties are shown as dotted lines in Fig. 2.2-1 and are given in Table 2.2-2.

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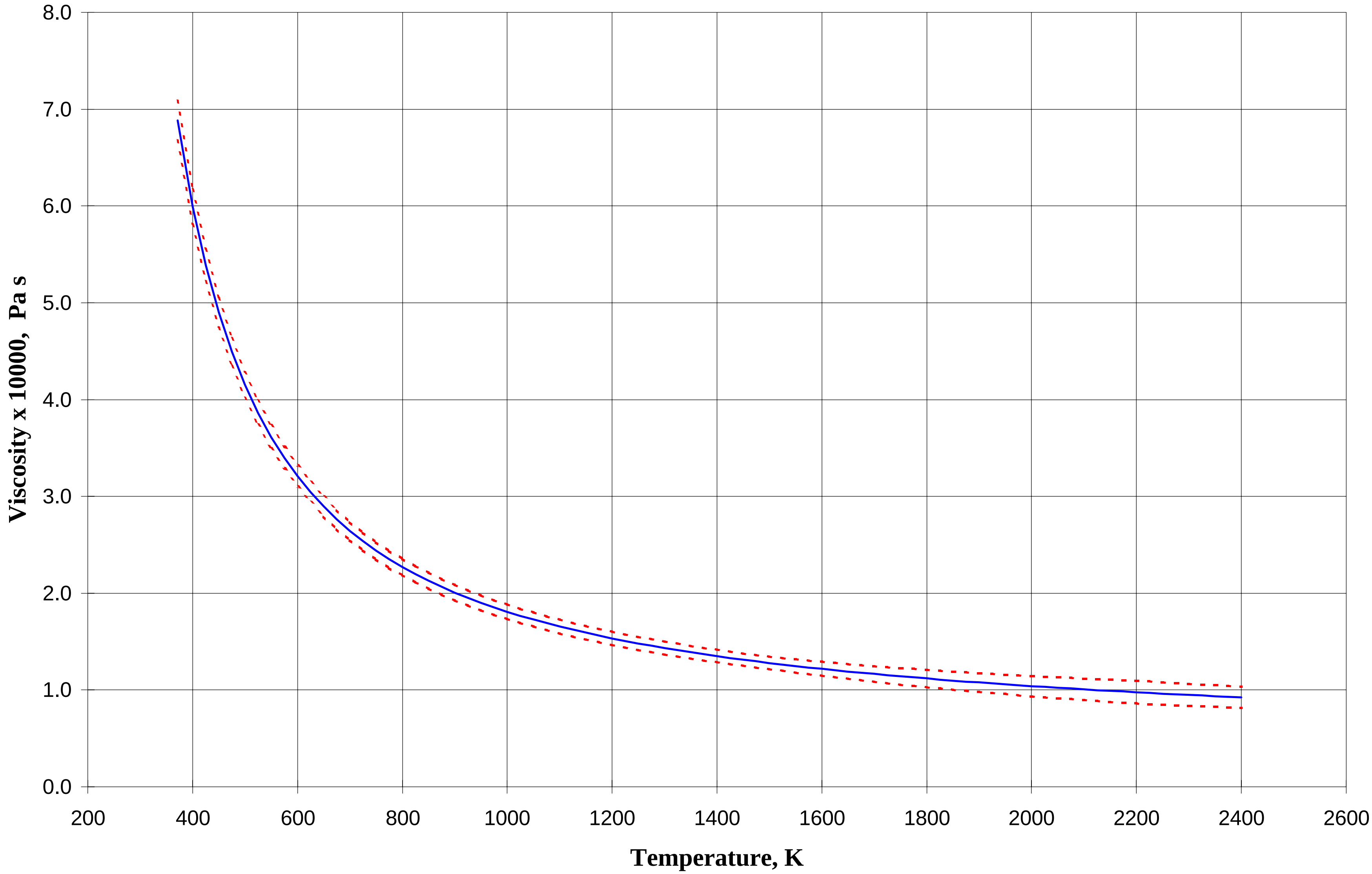

Fig. 2.2-1 Viscosity of Liquid Sodium

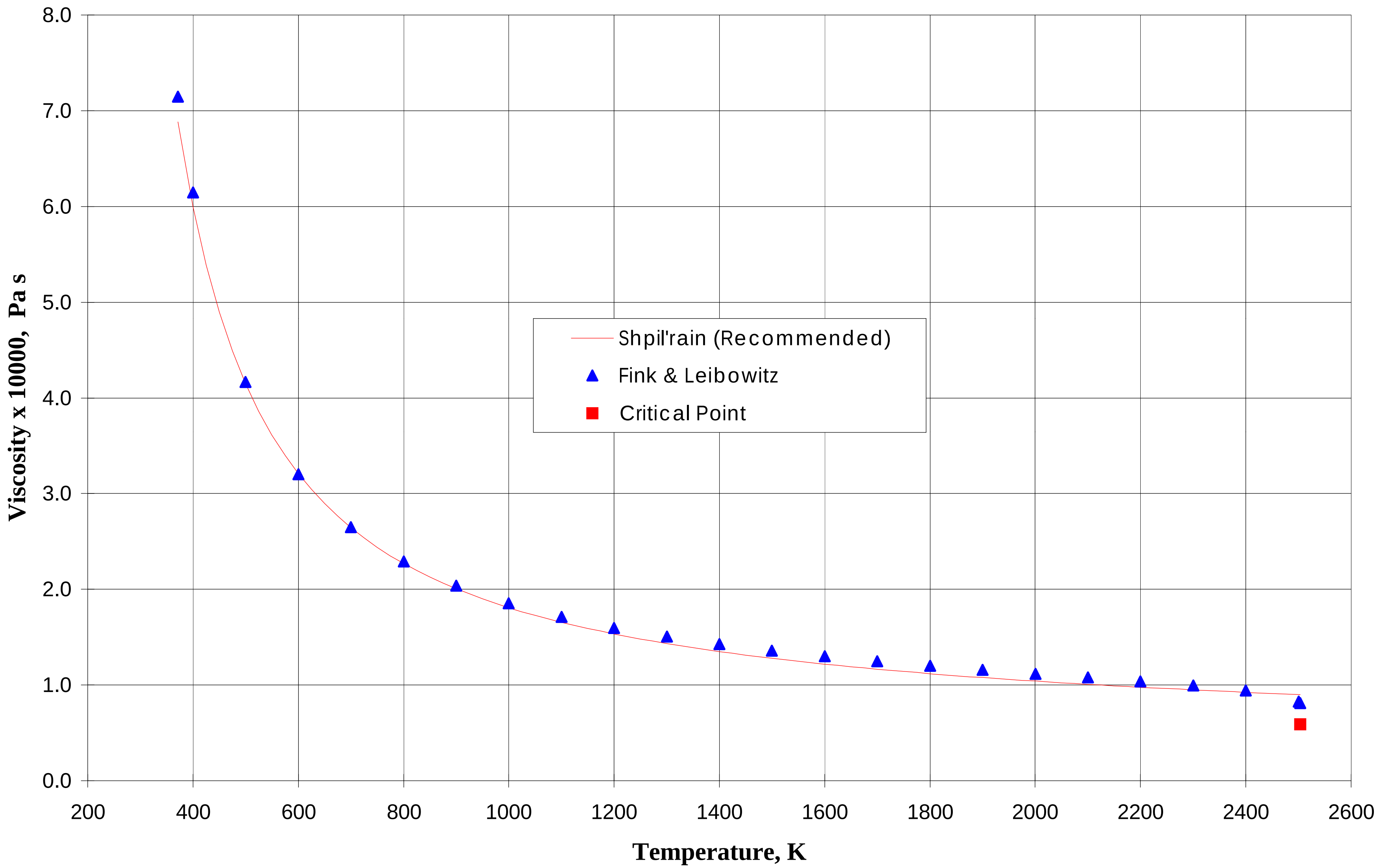

Fig. 2.2-2 Comparison of the Recommended Values for the Viscosity of Liquid Sodium with Values from Fink and Leibowitz

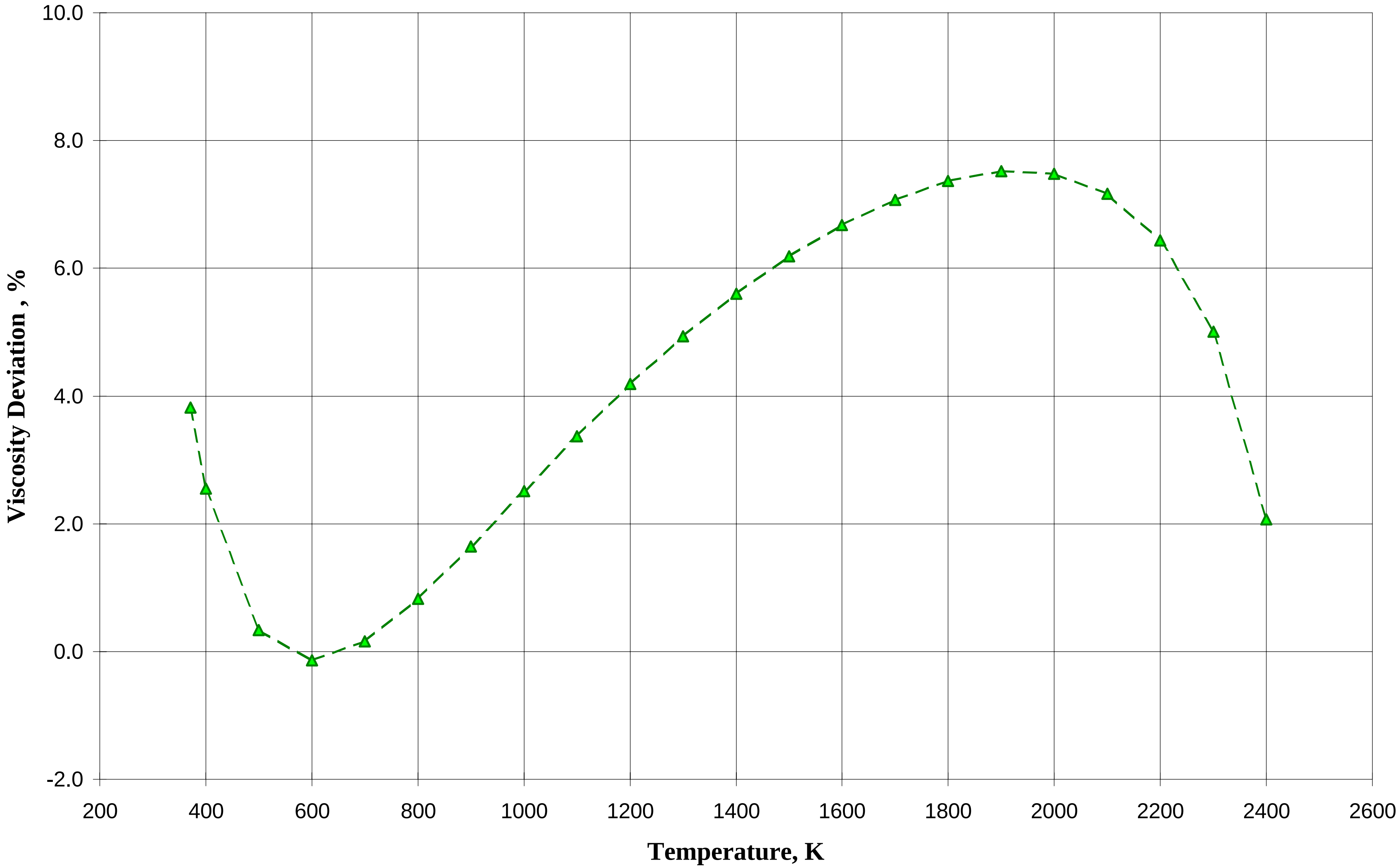

Fig. 2.2-3 Deviations of Values given by Fink and Leibowitz from Recommended Values of the Viscosity of Liquid Sodium